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PAPER

Simulation of gamma-ray distribution in rocks for determining the registration characteristics of measurement unit of horizontal borehole positional control system

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Abstract

Theoretical aspects of gamma-ray distribution in rock are described in the article. Information concerning the values of natural gamma radiation of rocks provides for the control of the drilling tool's orientation during horizontal drilling. A simulation of gamma-ray distribution in rock, based upon the example of western Siberian fields, has been made in a COMSOL Multiphysics interactive environment. Test results for a prototype, two-probe device for horizontal borehole positional control are contained in this document. The maximum distance for the registration of changes in the natural gamma radiation of rocks was determined. The attenuation coefficient for the natural gamma radiation of rocks introduced by the influence of a nonmagnetic drill collar was calculated. Practical advice for improvements in the registration characteristics of the prototype device is provided.

1. Introduction

Horizontal wells are wells with a high inclination angle (usually exceeding 85 degrees) that are drilled in order to increase oil and gas recovery from a producing formation by the placement of a longer horizontal wellbore section into the reservoir. This is their main distinction from extended-reach wells, which are high angle directional wells drilled to intersect the producing formation at a targeted point. Horizontal wells provide for a production increase due to a greater wellbore length entering the pay zone. This may be used to increase the cumulative field production or to reduce the number of wells needed to reach a targeted production level (Babadagli 2007). The successful employment of horizontal wells depends upon having a good description of the producing formation. This guarantees the optimal placement of the horizontal section within such a formation. Better borehole conditions reduce risks, produce higher drilling efficiency (Zhang *et al* (2008), Zhang *et al* 2015, Liu 2017). Unfortunately, forecasts concerning the depth or thickness of the producing formation are always vague due to uncertainties in the geological data and survey measurements (Liu *et al* 2013, Zohreh *et al* (2014)).

The most common reason for crossing the boundaries of an active reservoir during the process of horizontal drilling in oil and gas wells is associated with the low degree of accuracy in the spatial orientation of the bottom hole assembly with respect to the boundaries of the reservoir. Measurement systems are used during the process of drilling for wellbore positioning in horizontal-producing formations [see, for example, (Yang *et al* 2013, Zhang *et al* 2015). The spatial orientation of the wellbore with respect to the boundaries of the reservoir is determined by the registration of the natural gamma radiation of rocks.

To increase the accuracy of horizontal well positioning and to ensure a secure drilling tool orientation during horizontal drilling, the authors (Borikov *et al* 2013) suggested the use of a two-probe device for horizontal wellbore positional control, consisting of primary and directed measurement units of gamma-ray logging sensors. A performance evaluation of the device was conducted, based upon the results of a computer simulation, laboratory analysis and empirical research.

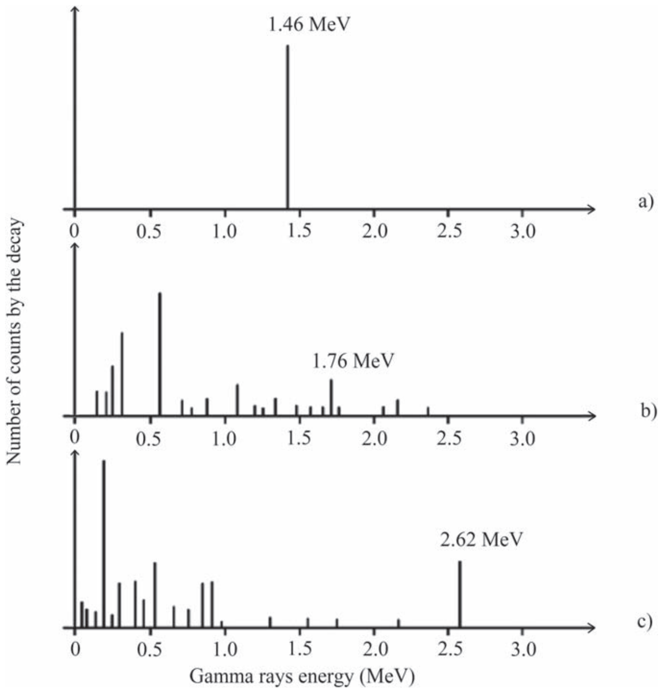

Figure 1. Gamma-ray spectrums of naturally-occurring decay chains: (a) ^{40}K, (b) ^{238}U and ^{226}Ra, (c) ^{232}Th.

2. Statement of the problem of a computer simulation of gamma-ray distribution

Gamma-ray probes measure radioactive emissions of natural origin. Such natural gamma radiation is emitted by radioactive elements found in sedimentary rocks, mainly by potassium (K), thorium (Th) and uranium (U). Potassium and thorium are closely associated with the presence of clay minerals in shale rocks (mudstone, illite, kaolinite and montmorillonite), while uranium may be found in sands, shale rocks, and certain hydrocarbon rocks. The radioactive emissions of potassium are strong, with a single energy level of 1.46 MeV. Thorium and uranium emit radiation within a determined energy range, but with a specific peak frequency. Such peaks are especially distinct at energy levels of 2.62 MeV for thorium and 1.7 MeV for uranium (figure 1) (Mengesha *et al* 2004).

The theoretical basis of the gamma method reflects its two aspects: litho-geochemical (regularities in the distribution of natural gamma-ray sources in rocks) and physical (regularities in the gamma-quantum generation and distribution in the heterogeneous-emitting and heterogeneous-absorptive system of the device-well-rock). These two aspects determine both the high informational value of the method and the difficulties of making a petro-physical interpretation of the measurement results.

3. Simulation of gamma-ray distribution in rock using as an example of western Siberian fields

The gamma-quantum distribution in rock may be characterized with partial differential equations (Kozhevnikov, Kalmykov (1997)). The COMSOL Multiphysics interactive environment uses a finite-element method of calculation. Since physical modes have already been integrated into the program, the goal of the research is to determine the correct PDE (Partial Differential equation) coefficients and simulation of the study subject. In this case, the process of gamma-quantum distribution may be described by using a diffusion equation, which is an approximation of the Boltzmann transport equation. The gamma-quantum diffusion equation is an aggregate of partial differential equations for groups of gamma quanta characterized by different energy levels. The PDE Modes Module of the COMSOL Multiphysics Program Package was used to solve the indicated problem. The classical Poisson equation was selected. This allows for the simulation of a point source at the beginning of the coordinate system, as well as the specification of medium characteristics.

Below, there is an overview of the system of diffusion equations for the density of the gamma-quantum flow in a two-group approximation for the reservoir (Medium I) and the overlaying formation (Medium II).

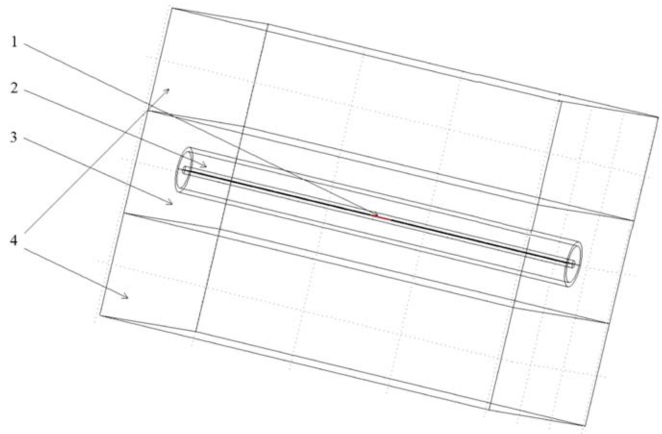

Figure 2. Three-Dimensional model of the producing formation in the process of drilling. 1–Two-probe device for horizontal wellbore positional control; 2–Bottom hole assembly; 3–Reservoir (Medium I); 4–overlaying formation (Medium II).

Medium I

$$\begin{array}{l} D_1^I \nabla^2 \Phi_1^I - \Sigma_{a1}^I \Phi_1^I + Q\delta(x, y, z, E) = 0 \\ D_2^I \nabla^2 \Phi_2^I - \Sigma_{a2}^I \Phi_2^I + \Sigma_{s1}^I \Phi_1^I = 0 \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ D_5^I \nabla^2 \Phi_5^I - \Sigma_{a5}^I \Phi_5^I + \Sigma_{s4}^I \Phi_4^I = 0 \end{array}$$

The border-line condition on the detector:

$$\Phi_n = 0, \text{ n} = 1, 2, \ldots 5$$

Medium II

$$\begin{array}{l} D_1^{II} \nabla^2 \Phi_1^{II} - \Sigma_{a1}^{II} \Phi_1^{II} + Q\delta(x, y, z, E) = 0 \\ D_2^{II} \nabla^2 \Phi_2^{II} - \Sigma_{a2}^{II} \Phi_2^{II} + \Sigma_{s1}^{II} \Phi_1^{II} = 0 \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ D_5^{II} \nabla^2 \Phi_5^{II} - \Sigma_{a5}^{II} \Phi_5^{II} + \Sigma_{s4}^{II} \Phi_4^{II} = 0 \end{array},$$

where x, y, z—are Cartesian coordinates, E—decay energy, $\sum$a—interaction cross-section of radioactive isotope with the detector, $\sum$s—absorption cross-section of radioactive isotope with the detector, Dj—gamma-quantum diffusion coefficients. n—decay number.

The border-line conditions on the medium distinction border are the conditions for the continuity of the gamma-quantum flow Φ_n.

The sources of the natural gamma radiation of rocks are radioactive potassium, thorium and uranium and their decay elements $(K^{Q\delta(x,y,z,E)}, Th^{Q\delta(x,y,z,E)}, U^{Q\delta(x,y,z,E)})$.

The cross-sections (group) Σ_{aj}, Σ_{sj}, as well as the diffusion coefficients D_j are formed in a special input file based upon ABBG ENDFB-6.8 libraries.

The calculation is made for the three-dimensional geometry (3D) (figure 2); the producing horizon (the reservoir sandstone of a finite length) during the process of well drilling and its bottom hole assembly are taken as the basis for the pattern. The device for horizontal wellbore positional control is integrated into the bottom hole assembly; the overlaying formation (mudstone, which is a solid, stone-like clay rock) of a finite length is determined as the source of the gamma quanta. The gamma-quantum flow at the border of the area is equal to the sandstone radioactivity. The values of the cross-sections of gamma-quantum absorption and scattering are selected as the values of the sedimentary rocks of the western Siberian fields.

A calculation array was generated, based upon the. submitted 3D-model; the quantity of finite elements amounted to 32,654. The calculation of the gamma-quantum emission intensity of the rocks is provided via the API (American Petroleum Institute) international measurement system. A three-dimensional model of the gamma activity in the producing horizon is constructed (figure 3).

The obtained radioactivity distribution model demonstrates that a device integrated into the bottom hole assembly and placed in the center of the producing formation will provide minimal values for gamma activity comparable to the values of the natural radioactivity of the reservoir. The gamma-ray energy is reduced when passing through dense materials. Pursuant to an analysis of the values of gamma activity in the producing horizon and within the nonmagnetic drill collar (NUBT-178, density 2 g cm^{-3}), it may be concluded that a nonmagnetic drill collar reduces gamma radiation by half.

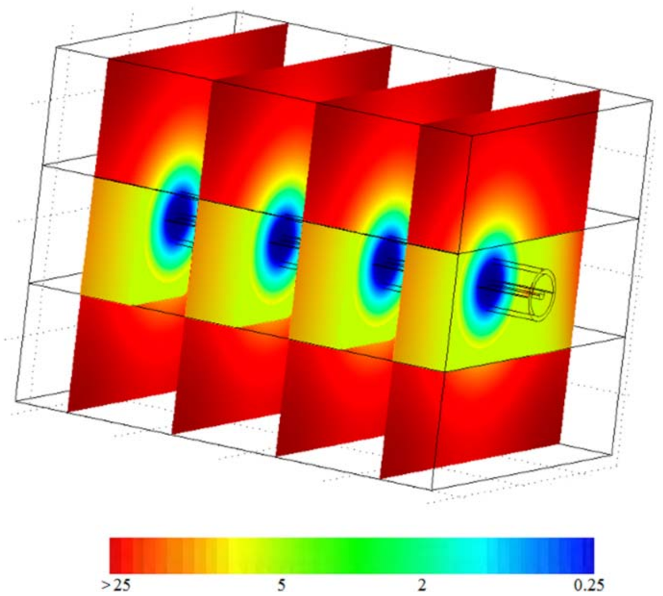

Figure 3. Three-Dimensional model of gamma activity distribution (API Units of Measurement) in the producing horizon.

The impact of the work environment upon gamma radiation is also worth noting:

- Weakening of gamma radiation in the wellbore environment due to a drilling mud effect. Barite ($BaSO_4$) is widely used as a substance for increasing the drilling mud density. Since barite is a material that increases density (approximately 4.5 g cm^{-3}), the gamma sensitivity is decreased with an increase in the drilling-mud density.
- The quantity of the registered gamma-ray impulses increases with a decrease in the distance between the sensor and the wellbore wall, and vice-versa. This may take place as a result of the installation of a sensor having a different diameter during alterations in the bottom hole assembly, provided that the borehole diameter remains unchanged.
- Since the gamma radiation of elements in the formation is of a random nature, a very short measurement period may be insufficient for the determination of a statistically accurate value between measurements, and may result in a curve that is not representative of the actual pattern. A very long measurement period may result in the washing out of the borders of the bottom formation because of the averaging of the very large number of impulses from one data point, and may result in a curve with untraceable characteristics.

In general, it may be said that the device measures radioactive emissions of natural origin within a 50-centimeter zone of the detector's location, with consideration for any impact upon the readings from the bottom hole assembly or the drilling mud. The values of radioactivity sharply grow when the bottom hole assembly approaches the boundaries of the reservoir. The boundary of the reservoir in respect to the bottom hole assembly may be accurately determined by use of the directed measurement unit of the gamma-ray logging sensor.

4. Testing of a prototype two-probe device for horizontal wellbore positional control

A two-probe device for horizontal wellbore positional control is suggested for controlling the drilling tool's orientation during horizontal drilling (figure 4). The device has main and directed measurement units for gamma-ray logging sensors installed in a measure-while-drilling casing shell. The directed measurement unit of the gamma-ray logging sensors is placed in a lead casing with a window for the registration of the directed gamma radiation, which is physically correlated to the toolface. The indicated measurement units are installed in the spaces in the casing of the gamma measurement module (Golodnykh, Borikov (2013)).

The transformation of gamma rays into acceptable electrical signals occurs in the measurement unit of the device for horizontal wellbore positional control, which consists of three main parts: a scintillation detector (a sodium iodide crystal NaI(Tl)), a photomultiplier tube and a transimpedance amplifier.

The prototype two-probe device for horizontal wellbore positional control (hereinafter, referred to as the 'device') was developed to obtain experimental data. It is a module that is made based upon a NaI(Tl) scintillator

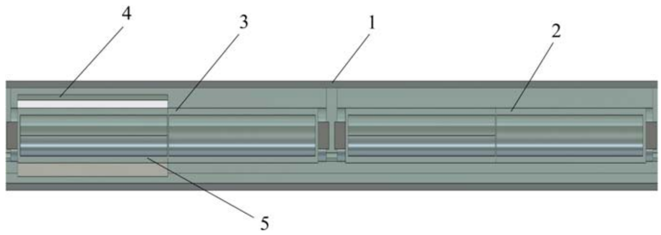

Figure 4. Layout of the casing of the gamma measurement module with units of gamma-ray logging sensors: 1–Casing of the gamma module; 2–Main sensor; 3–Directed sensor; 4–Lead casing; 5—Window.

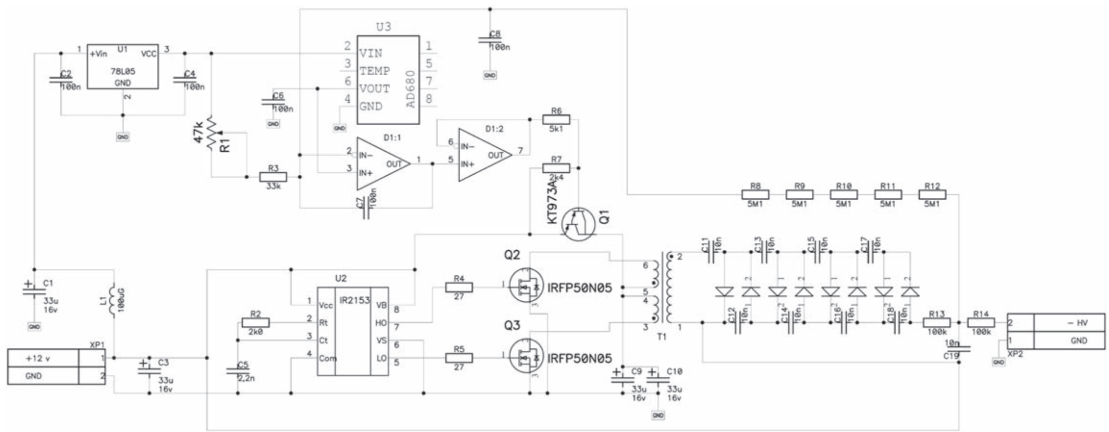

Figure 5. High Voltage supply for PEM.

—SDN.52.16.40 and a photo-electronic multiplier (PEM) FEU-86, with a signal separator and amplifier. An ATMEL AT89C2051 microcontroller performs online data processing and data transfer to a PC (figures 5 and 6).

Once a charged particle gets into a scintillator, it causes ionization and excitation of its molecules. Then, the molecules transit into a stable state by emitting photons, resulting in scintillation. A part of photons is detected by a photo-electronic multiplier (PEM). The high voltage supply for the PEM are shown on figure 5.

In scintillation counters there is a possibility of emergence of a large number of pulses, which are not connected to the registration of ionizing particles, at the output of the PEM. These pulses have small amplitude and are called noise pulses. In order to offset PEM own noise pulses, a discriminator/comparator, which skips pulses below a preset threshold, is included into the recording circuit (figure 6). At the output of discriminator/comparator, the pulse passes through a pulse normalization scheme (where pulse duration is normalized according to the characteristics of pulse counter), the output of which produces pulses with a guaranteed minimum width suitable for registration by a microcontroller.

The microcontroller counts pulses with the discretization of 1 s, and writes data to a flash memory card. An external PC can be connected through a COM port XP102.

The following problems were to be solved during the process of the development and operation of the prototype two-probe device for horizontal wellbore positional control:

- Adequate assessment of the measurement of the natural gamma radiation of rocks per time unit by the main measurement unit of the gamma-ray logging sensors (omnidirectional);
- Adequate assessment of the measurement of the natural gamma radiation of rocks per time unit by the directed measurement unit of the gamma-ray logging sensors;
- Online transfer of the measurement data to a PC;
- Determination of the maximum distance for the registration of changes in the natural gamma radiation of rocks;
- Determination of the attenuation coefficient caused by the bottom hole assembly;

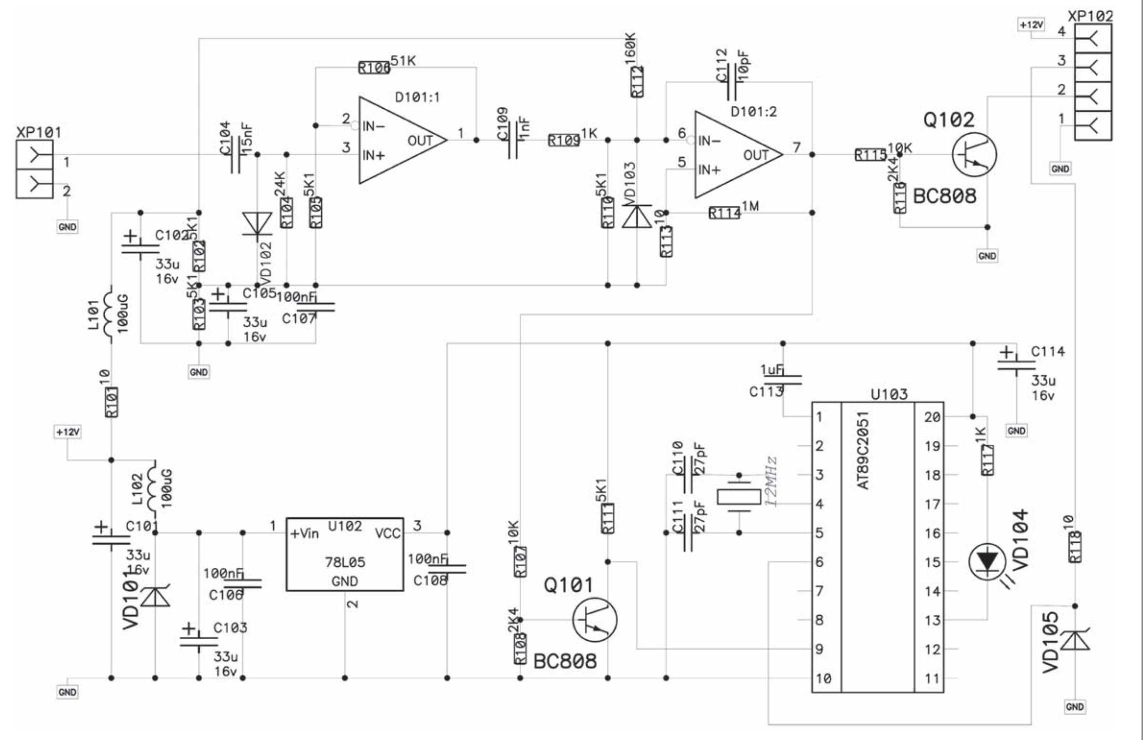

Figure 6. Data Processing and Transfer to PC.

- Determination of the registration characteristics of the directed measurement unit of the gamma-ray logging sensors.

Measurements of the gamma activity were carried out in a laboratory environment via the use of a ^{22}Na source, and in the field via the use of an ^{241}Am source. A digitizing time was selected that was equal to one second; the unit of measurement of the gamma activity was accordingly imp/s.

During the operation of the prototype device, research into the gamma activity registration with consideration for the distance from the ^{241}Am source was held in the field. Three scenarios were simulated:

- An approach to the boundary of the reservoir during the process of gamma-ray registration by the main gamma probe;
- An approach to the boundary of the reservoir during the process of gamma-ray registration by the directed gamma probe;
- An approach to the boundary of the reservoir during the process of gamma-ray registration by a gamma probe directed from the gamma-ray source.

During the course of research, the background gamma radiation of the rocks amounted to 30 pulse/s. The registered gamma radiation at a distance of 0.9 meters from the source was 304 pulse/s. This ten-fold increase in the gamma background shows that the maximum distance for the registration of changes in the natural gamma radiation of rocks is 0.8–1 m, without consideration for any attenuation caused by the bottom hole assembly.

The directed module for gamma-ray registration was placed in a lead-casing shell with a window for the registration of the gamma-quanta in the drilling direction (figure 7).

An experiment was conducted based upon the example of the prototype device. During the process of this experiment, the dependence of the gamma-ray registration by the directed measurement unit of the gamma-ray logging sensor upon the window size (from 45° to 60°) was identified. The difference between the values of the gamma-quantum registration by the directed unit and the unit for the registration of the general gamma-ray background, which amounted to 30%–52% of the value of the main measurement unit of the gamma-ray logging sensors, was assayed (figure 8).

The laboratory analysis, with consideration for the gamma activity registration by the directed measurement unit of the gamma-ray logging sensors of the device, was conducted during the process of turning the sector around its axis at a specified distance from ^{22}Na source (figure 9).

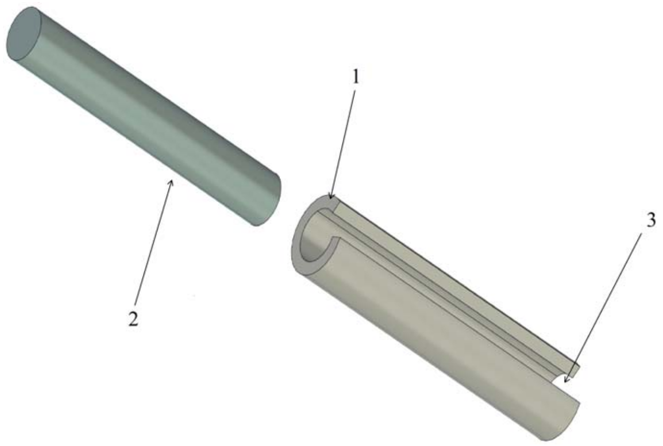

Figure 7. Sectional diagram of the directed measurement unit of gamma-ray logging sensors. 1–lead casing shell, 2–NaI(Tl) scintillator, 3–Window for gamma-quantum registration.

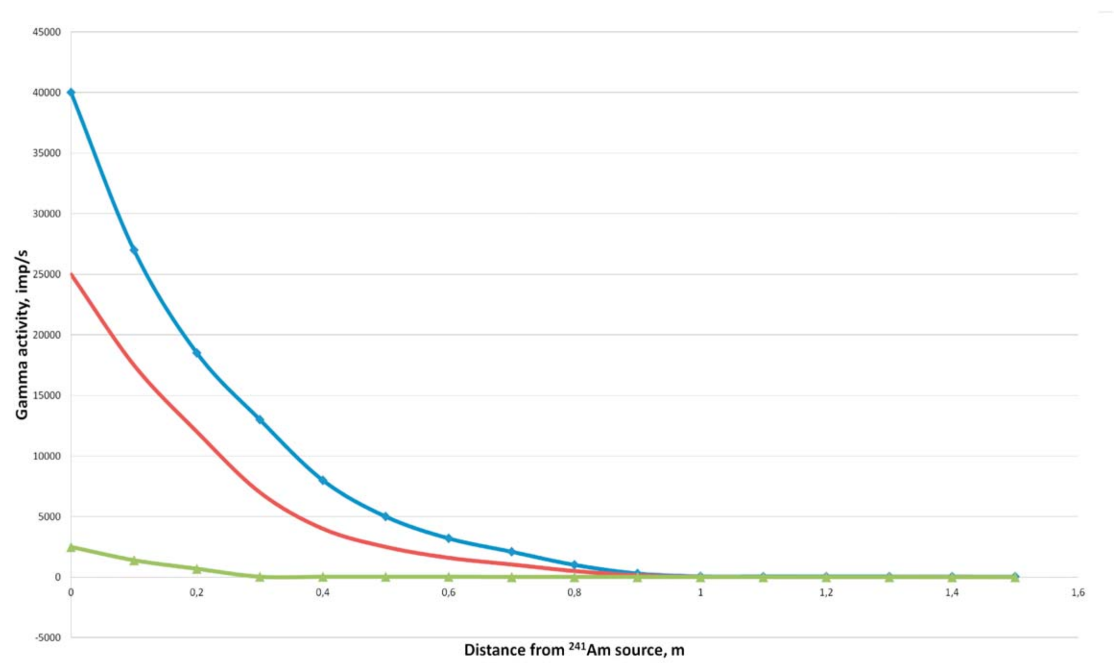

Figure 8. Gamma-ray intensity in rock depending upon the distance from the source.

The gamma activity distribution during the process of turning the sector of the directed gamma unit demonstrates that the value of the gamma activity at the same distance from the gamma-ray source changes by almost half. The minimum values have been registered with the sector directed from the source (75 pulse/s); the maximum value (135 pulse/s) has been registered with the sector directed to the ^{22}Na source.

Gamma radiation demonstrates a significantly higher penetration when compared to alpha or beta radiation. Having a zero rest mass, the gamma quanta do not slow in the medium, which is why they are either absorbed or dispersed when passing through the substance. When gamma radiation of an I_0 intensity reaches an absorbent with an L thickness, the I intensity of the radiation passing through the absorbent is described via the exponential expression:

$$I = I_0 \cdot e^{\mu_i L},$$

where μ_l is the linear attenuation coefficient expressed in cm^{-1}.

The ratio I/I_0 is known as the gamma-ray transmission coefficient. This transmission coefficient increases with an increase in the gamma-ray energy level and decreases with an increase in the absorbent's thickness. The

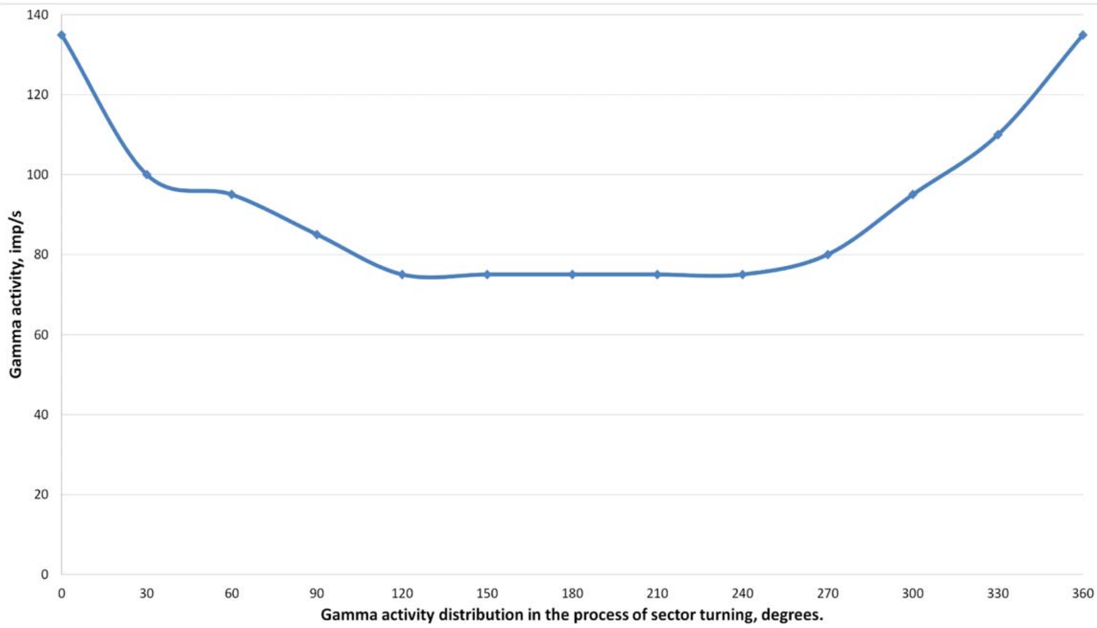

Figure 9. Gamma activity distribution in the process of sector turning.

gamma radiation of steel ($\mu_l = 0.33$ at an energy of 2 MeV), with a steel thickness of 2 cm (comparable to the thickness of the bottom hole assembly wall), will decrease by 30% of the original value.

As has been previously determined, the maximum distance for the registration of changes in the natural gamma radiation of rocks is 0.8–1 m, without consideration for the impact of any attenuation caused by the bottom hole assembly. Thus, the maximum distance for the registration of changes in the natural gamma radiation of rocks, with consideration for the impact caused by the bottom hole assembly, equals 0.56–0.7 m.

5. Conclusions

We simulated gamma-ray distribution in rocks for determining the characteristics of horizontal borehole position control system using incorporated in COMSOL Multiphysics partial differential equation method. The advantage of modeling gamma-quanta distribution by using partial differential equations over alternative modeling methods, based on the numerical solution of the kinetic equation, is the convenience and adaptability of partial differential equations to solving multidimensional boundary problems in multicomponent media. The unique advantage of this method is the possibility of efficiently parallelizing computations on modern multiprocessor computers and the application of methods for reducing statistical error of the results are the main differences between partial differential equation and normal simulation methods.

An adequate assessment of the measurement of the gamma radiation of rocks per time unit by the main and directed gamma probes was conducted, the maximum distance for the registration of changes in the natural gamma radiation of rocks was determined, and the coefficient attenuation caused by the bottom hole assembly was identified during the process of the development and testing of the prototype two-probe device for horizontal wellbore positional control.

Pursuant to the results of testing for the prototype device, the sensibility of the main measurement unit of the gamma-ray logging sensors will make it possible to determine the growth of the total gamma background at a distance of 0.56 meters from the crossing point of the boundaries of the reservoir, with consideration for the impact of the bottom hole assembly. The location of the boundary of the reservoir may be determined via the use of the directed measurement unit of the gamma-ray logging sensors, with a guaranteed level of accuracy at a distance not exceeding 0.4 meters, with consideration for the impact of the bottom hole assembly.

The dependence of the gamma-ray distribution upon the distance from the source was demonstrated, based upon the example of western Siberian fields. Simulation modeling of the gamma activity distribution in producing horizons was also conducted for a finite-length producing horizon, based upon the example of western Siberian fields. The simulation results compare favorably with the experimental data and complement them.

The design for the prototype two-probe device for horizontal borehole positional control is fully operational, and makes it possible to determine the spatial orientation of the drilling tool in respect to the boundary of the reservoir via an increase in the general gamma background of the rocks.

The registration characteristics of the main and directed gamma probes of the prototype device may be increased by:

- Increasing the window (sector) of the gamma-quantum registration unit up to 90°;
- Use of a larger-volume scintillator;
- Implementation of a FEU with a higher light-anodic sensibility (HAMAMATSU R3991A-31).

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